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Simultaneous reduction of CO and NOx emissions as well as fuel consumption by using water and nano particles in Diesel–Biodiesel blend

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ABSTRACT

Restrictive emission regulations and climate change are the main motivations for improving engine combustion characteristics to decrease engine-out emissions and fuel consumption. Fuel additives are effective solutions to improve fuel properties to address these challenges. In this study, simultaneous application of water and cerium oxide nanoparticles in diesel-biodiesel fuel blend on performance and emission characteristics of a single cylinder diesel engine operated at start of injection of 20 before top dead center was experimentally investigated. Achieved results showed that the B5W7m fuel emulsion (B5 containing 7% water and nanoparticle) enhanced brake thermal efficiency by more than 13.5 and 6% compared to B5W7 and B5, respectively. Furthermore, the B5W7m reduced brake specific fuel consumption by8% and 23% *vs.* those of B5 and B5W7, respectively. CO emission was considerably decreased by using B5W7m, i.e., by 42% and 3% compared with B5W7 and B5, respectively. Combustion improvements observed could be attributed to the catalytic effect of cerium oxides nanoparticles. On the other hand, addition of 90 ppm CeO_2 into the B5W7increased NOx emission by about 14%, this value was still 21% lower than the NOx emitted by B5 combustion though.

1. Introduction

Increasing energy consumption and engine-out emissions are two ongoing concerns motivating researchers to find more reliable eco-friendly energy solutions (International Energy Outlook, 2013). Combustion of biodiesel instead of conventional diesel in compression ignition (CI) engines could be a feasible alternative to meet the increasingly stringent mandates imposed for emissions control. Biodiesel has similar properties to those of diesel fuel while it is associated with cleaner combustion (Gharehghani et al., 2017). More specifically, some researchers have shown that use of biodiesel-diesel blends would result in more favorable engine emissions parameters, such as reduced CO and HC emissions as well as lower particular matters (PM) (Esteves et al., 2018; Caliskan, 2017). In spite of such favorable features, several studies have claimed an unfavourable increase in nitrogen oxides (NOx)emission in response to the combustion of biodiesel blends when compared with neat diesel combustion (Dharma et al., 2017; Miri et al., 2017). For instance, Can et al. (2017) investigated the effects of canola biodiesel blends on the combustion and exhaust emissions of single cylinder diesel engine. Their results revealed that biodiesel blends resulted in a higher NO_x emission of 8.9% compared to neat diesel.

Therefore, over the last years, many strategies including the application of fuel additives have been used to reduce the excess

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NOx emissions associated to biodiesel inclusion in diesel fuel (Najafi, 2018). Addition of water in biodiesel-diesel blends has been offered as an effective, well accepted strategy for decreasing NOx emissions (NurunNabi et al., 2017). Moreover, researchers have argued that water-diesel emulsion (WDE) is the most practical/reasonable strategy for using water in internal combustion engines, because of its huge effect on decreasing exhaust emissions while no engine modifications would be required (Yang et al., 2013). Some studies have proven that NOx and PM emissions were simultaneously decreased due to combustion of WDE fuels with no considerable negative effect on brake specific fuel consumption (BSFC) (Mazlan et al., 2018). On the other hand, it should be noted that the high latent vaporization heat of water could lead to lower in-cylinder temperatures consequently elevating CO and HC emissions (Khalife et al., 2017a). Experimental investigation of Yang et al. (2013) revealed that 15% water content in diesel fuel resulted in 31% reduction in NOx emission with negligible increases in BSFC (Yang et al., 2013). On the contrary, some researchers have reported increases in BSFC by adding water to diesel-biodiesel fuel blends, depending on the volumetric content of water (Nanthagopal et al., 2018; Zare et al., 2017).

Metal-based additives are also considered among promising combustion enhancing materials reportedly used in CI engines (Ashok et al., 2017). Effect of zinc oxide nanoparticles as fuel additive on the emission characteristics of a dual-fuelled engine (i.e., hydrogen and jatropha methyl ester biodiesel) was investigated by Javed et al. (2016). Their results showed that the size of nano particles influenced the brake thermal efficiency (BTE) of the engine. They claimed that B30–ZnO40 nm had almost the same BSFC as that of neat diesel, indicating an improvement in combustion despite B30–ZnO40 nm having a lower calorific value than neat diesel. Diesel fuel containing nano-aluminum particles demonstrated a higher heat release rate than neat diesel and lower NOx emission (Kao et al., 2008). Jiaqiang et al. (2018) showed that aqueous cerium oxide nano-fluid fuel additives, even at 50 cc of CeO_2per liter, considerably increased the performance of CI engines, i.e., improved BTE and BSFC. Moreover, HC and CO emissions were reduced by this addition in comparison with no CeO_2 addition. A study on performance, combustion and emission behavior of a diesel engine powered by novel nanonerium oleander biofuel showed drastic reductions in HC and CO emissions compared with neat diesel (Dhinesh and Annamalai, 2018).

Based on the above-mentioned literature, the addition of water into diesel-biodiesel fuel blends would cause higher fuel consumptions as well as higher level of HC and CO emissions. However, the mixture of metallic-based additives with water-diesel (biodiesel) emulsion has been shown to act as an efficient alternative to water addition in CI engines, while concurrently maintain the NOx reducing characteristic of water addition (Khalife et al., 2017b). Experimental investigation by Vellaiyan and Amirthagadeswaran (2018) on Zinc oxide incorporated water-in-diesel emulsion fuel showed that the addition of ZnO (50 and 100 ppm) to the water-diesel emulsion (10% water) had the potential to reduce HC, CO, and NOx emissions simultaneously. Khalife et al. (2017b) investigated simultaneous addition of 3, 5, and 7 wt.% water and cerium oxide nanoparticles into diesel-biodiesel blends to understand the collective effects of these two additives on engine performance at the start of injection of 38 before top dead center (BTDC) and reported promising findings for low-level water inclusion, i.e., 3%. However, the results achieved for the highest water inclusion rate of 7 wt.% were not satisfactory, higher water inclusion rates might be more economically favorable though. Overall and as thoroughly discussed in the aforementioned literature, the mixture of water and metal-based additives in diesel-biodiesel fuel blends could be generally considered as combustion enhancer in compression ignition engines but more investigations are required to further shed light on the various aspects of this promising strategy. Thus, the present study was set to further experimentally investigate the effects of CeO_2 (90 ppm) addition into B5, containing water (7% wt.) on the performance and emission characteristics of a single cylinder diesel engine operated at start of injection of 20 BTDC.

2. Experimental procedure

2.1. Biodiesel production and fuel samples preparation

Biodiesel production, as well as fuel samples preparation, has been described in detail in our previous publications (Gharehghani et al., 2017; Khalife et al., 2017b). Emulsification of water and cerium oxide in B5 was achieved by including 75 ml of a 1:2 blend of two known surfactants, i.e., Tween 80 and Span 80 (Merk, Germany), respectively, into B5 prior to the addition of water and the metal-based catalyst. Finally, the prepared emulsions were stabilized by using a Polytron® homogenizer (Switzerland) at room temperature for 15 min (Khalife et al., 2017b).

2.2. Setup and method of experiments

Experiments were conducted on a single-cylinder Ricardo E6 diesel engine, while its compression ratio was variable (Max. CR 22). Table 1 and Fig. 1 present the engine specifications and its schematic diagram, respectively. The engine displacement volume was 507 cc, with a bore and stroke of 76.2 and 110 mm, respectively. An electrical dynamometer loaded the engine, rated at 22 kW and 420 V. The in-cylinder pressure and crank angle position were measured by a piezo-electric type pressure transducer (QC43D, AVL), and a magnetic rotary encoder (MES-2500D-T, Fotek), respectively. The latter recorded the crank angle and the resolution was 2500 pulses per revolution (PPR).

A fuel flow meter (AVL-735) was employed to measure fuel consumption. A Lambda sensor was installed in the exhaust manifold to monitor the Air Fuel Ratio (AFR). NOx, CO, CO_2, O_2, and HC concentrations were determined by an AVL DiGas 4000 emission analyzer. The accuracy and resolution of the analyzer are reported in Table 2. Before beginning the test procedure, the initial calibrations of the emission equipment were done. After the warm up run, the pre test procedures are done to determine operating conditions of the engine and the stabilization time has been identified. Ahead of testing different fuel samples, the system allowed to remain stable for certain time which reduces the error in calibration.

The properties of the sample fuels are provided in Table 3. The engine was run at 1200 rev/min with 25%, 50%, 75%, and 100% of engine full load. Conventional combustion mode and a steady state condition were maintained. Two hundred continual cycles were examined to evaluate the cycle-to-cycle variations, and their means were used to analyze the heat release rate and combustion characteristics. The flowchart of the experimental procedure is shown in Fig. 2.

Table 1
Specifications of Ricardo E6 engine.

Parameter	Specification
Engine type	Single cylinder Ricardo E6
Displacement volume	507 cc
Stroke	110 mm
Bore	76.2 mm
Compression Ratio	17:1 (Max. CR 22)
Injection Timing	Variable 20°-45° BTDC

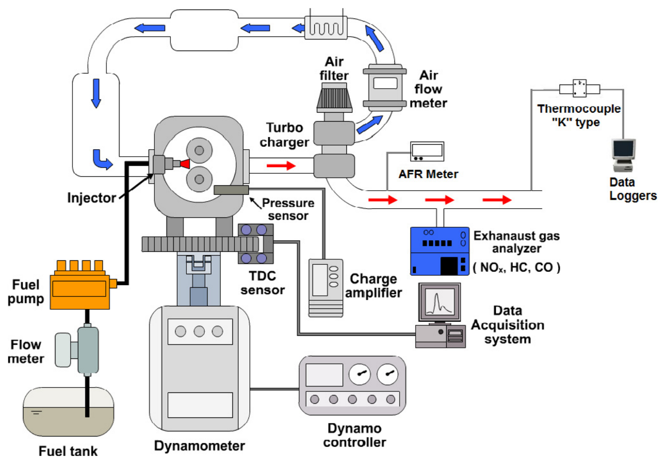

Fig. 1. The schematic diagram of the setup used for combustion experiments.

Table 2
AVL DiGas 4000 gas analyzer specifications.

Species	Resolution	Accuracy
CO	0.01% Vol.	±1%
CO_2	0.1% Vol.	±1%
HC	1 ppm	±1%
NOx	1 ppm	±1%
O_2	0.01% Vol.	±1%
λ-calculation	0.001	±1%
Engine Speed	10 rpm	±1%

Table 3
The properties of the investigated fuel blends.

Fuel type	Kinematic viscosity (mm^2/s)	flash point (°C)	Calorific Value (MJ/kg)
D	2.84	74	45.221
B5	2.9	82	44.572
B5W7	3.92	74	42.488
B5W7m	3.88	77	42.382

Table 4
Measurements of uncertainties in the calculated results.

Parameter	Resolution	Accuracy	Max. Uncertainty
Fuel Consumption	–	±0.01 kg/hr	±0.1%
In-cylinder Pressure	–	±0.1 bar	±0.2%
Temperature	–	±0.1 °C	±0.2%
Emissions (HC, NOx)	1 ppm	±1%	±0.1%
Emissions (CO, CO_2)	0.01% Vol.	±1%	±0.1%
Engine Speed	10 RPM	±1%	±0.1%

2.3. *Error analysis and uncertainty*

Errors in experimental measurements may be attributed to operators and devices. The latter could be related to nonlinear operation of devices as well as miscalibration. Given these errors, measurements obtained from the experiments cannot be considered complete and accurate unless certain statistical and mathematical methods are used to minimize them. The general method is to use repeated measurements and determine minimum error rate for obtaining desired results. As reported by previous investigations, the following three methods are considered for estimating errors associated with such systems (Salahi et al., 2017; Kakoee et al., 2018):

A) Error estimation of primary parameters: the first group of parameters measured directly is pressure, temperature, mass flow of air, fuel mass flow, as well as the species in the exhaust gases. The repeat testing strategy with internal error analysis has been used for these parameters.
B) Error estimation of secondary parameters: external error analysis strategy is used for secondary parameters, which are lambda and specific emissions obtained using primary parameters.
C) Estimation of the errors caused by cyclic variations: the third group of parameters is those whose changes in each cycle are due to a small deviation of the mean value generated due to cyclic variations. Minimization of error in these parameters has been done by their repeated measurements. In this way, measurements are performed 200 times at a point and recorded for a parameter, and then the average of these values is taken into account this group of parameters. Measurements of uncertainties in the calculated results are shown in Table 4.

3. Results and discussion

Investigating the impact of simultaneous application of CeO_2 nanoparticles and water (7%) as additive on the combustion characteristics as well as engine-out emissions of diesel-biodiesel fuel blend was the main purpose of the current work. The standard first-law analysis was used to calculate the heat-release rate (HRR), and to evaluate the engine operating conditions from the measured pressure data (Heywood, 1988), as follows:

$$\frac{dQ_{combustion}}{d\theta}=\frac{dQ_{net}}{d\theta}+\frac{dQ_{wall}}{d\theta}=\frac{1}{1-k}V\frac{dP}{d\theta}+\frac{k}{1-k}P\frac{dV}{d\theta}+\frac{dQ_{wall}}{d\theta} \quad (1)$$

where $\frac{dQ_{net}}{d\theta}$ denotes the net heat release rate and $\frac{dQ_{wall}}{d\theta}$ resembles the rate of heat transfer to the walls while the Woshni correlation (Gharehghani et al., 2017) was used to calculate this factor. Moreover, V standing for the instantaneous cylinder volume was calculated with geometric correlation while k is the specific heat ratio ($\frac{C_p}{C_v}$) (Heywood, 1988).

3.1. *Combustion characteristics of various fuel blends*

HRR and in-cylinder pressure for various fuelling strategies are compared in Fig. 3. Data acquisition was completed while the engine was working under 100% of engine full load, running with the investigated fuel blends.

Biodiesel has a higher cetane number while its molecular structure contains oxygen; these factors collectively leading to a more rapid combustion of biodiesel-diesel blends (Ozener et al., 2014) and inconsequence, a higher in-cylinder pressure for B5 fuels is expected. Water addition could affect the specific heat capacity of the mixture (Fahd et al., 2013), and as observed in the present study, in case of B5W7 fuel blend, a lower in-cylinder pressure was recorded due to a lower in-cylinder temperature. Based on the data presented in Fig. 3, the addition of CeO_2 nanoparticles in the B5W7 fuel blend (i.e., B5W7m) led to superior in-cylinder pressure values (comparable with the in-cylinder pressure of B5). A possible reason for explaining this outcome is as follows: at higher temperatures during combustion, the cerium oxide nanoparticles reacted with water molecules generating hydrogen, which in turn, promoted the combustion process (Khalife et al., 2017a). Based on Equation (1), higher pressures lead to higher HRRs and by calculating the HRR using the experimental

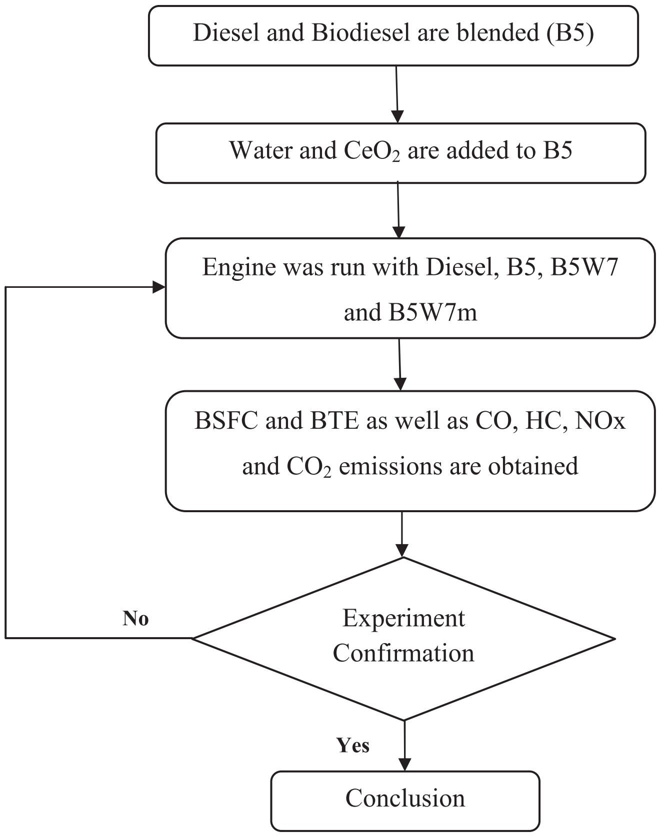

Fig. 2. Flowchart of the experiments procedure.

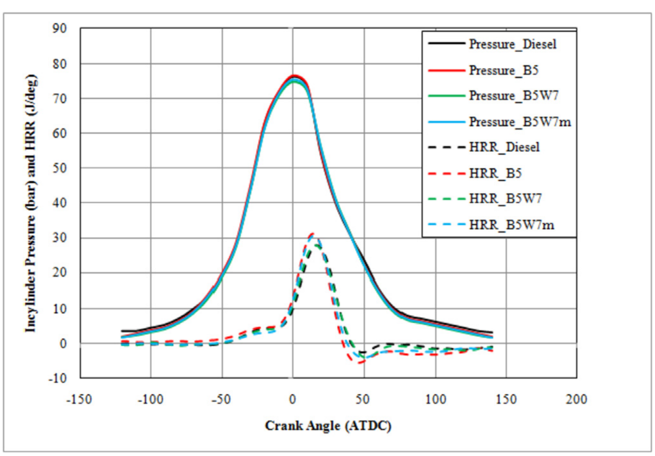

Fig. 3. Comparing in-cylinder pressure and HRR at 100% load.

data of in-cylinder pressure (Fig. 3), B5W7m combustion led to the highest HRR. This behavior was consistent with the trend of in-cylinder pressure.

The exhaust temperature of various fuel blends is graphed in Fig. 4 as a function of engine load. As shown in the Figure, B5 generated the highest temperature at all loads. The oxygen content of biodiesel is comparatively higher and this must have led to an advanced combustion, a higher in-cylinder temperature, and exhaust temperature. Based on Fig. 3, water addition decreased the in-cylinder temperature (pressure), which reduced the exhaust temperature to the lowest value for B5W7. The exhaust temperature for this fuel blend was around 21%lower than that ofB5. On the other hand, CeO_2 nanoparticles exhibited a catalyzing impact and increased the cylinder temperature, which in turn led to a 16% increase in exhaust temperature of B5W7m fuel blend compared to B5W7.

Fig. 5 shows the energy balance for diesel, B5, B5W7, and B5W7m fuel blends at 100% engine load. Energy balance calculations were reported in detail in our previous publication (Gharehghani et al., 2013) while required adjustments are used for the current investigation.

Based on the energy balance analysis, water inclusion declined the engine thermal efficiency (i.e., work) because of its adverse effects on combustion characteristics (lowering the combustion temperature) (Subramanian and Ramesh, 2002). While the addition of CeO_2 nanoparticles extremely enhanced the thermal efficiency. Due to their large surface area/volume ratio, the added metal-based CeO_2 nanoparticles acted as a catalyst throughout the combustion process (Anbarasu et al., 2016). In addition, the catalytic activity of the CeO_2 nanoparticles must have improved the 'micro-explosion' phenomenon, which is, associated with positive effects on combustion characteristics (Aghbashlo et al., 2017).

BTEs of neat diesel, B5, B5W7, and B5W7m are compared in Table 5. BTE of neat diesel was slightly lower than that of B5 at all loads. The higher thermal efficiency and enhanced combustion phenomenon of the biodiesel-diesel blend could be ascribed to the oxygen content of biodiesel and thus, its higher quality of ignition (Ozener et al., 2014). Water addition decreased the thermal efficiency at all engine loads, as presented in Fig. 3. In contrast, cerium oxide nanoparticles increased thermal efficiency considerably because of their positive effect on the combustion process. Based on Fig. 5 and Table 5, compared to B5W7 and B5, the B5W7m fuel blend augmented BTE by more than 13.5% and 6%, respectively. The higher peak cylinder pressure and faster HRR of B5W7m fuelling case as presented in Fig. 3, could be the explanation for the higher BTE value of this fuel blend.

BSFC values of the various fuel blends are presented in Fig. 6 at all engine loads. Based on the presented results in Fig. 6, the lower caloric value of biodiesel led to higher BSFC value for B5 compared with neat diesel (Gharehghani et al., 2017; Aghbashlo et al., 2017). In addition, addition of water to B5 caused a higher BSFC value compared with B5 and neat diesel fuelling cases. Presence of water in biodiesel-diesel blend reduces the heating value of the mixture and as a result, higher BSFC values should be expected (Liang et al., 2013). On the other hand, by adding the CeO_2 nanoparticles into

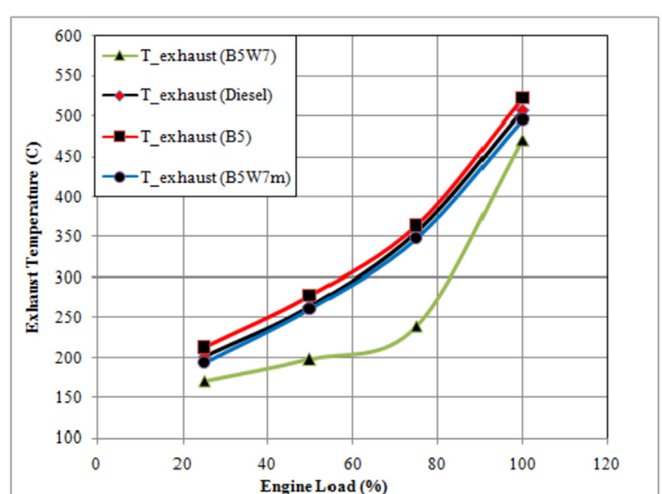

Fig. 4. Exhaust gas temperatures for various fuelling cases.

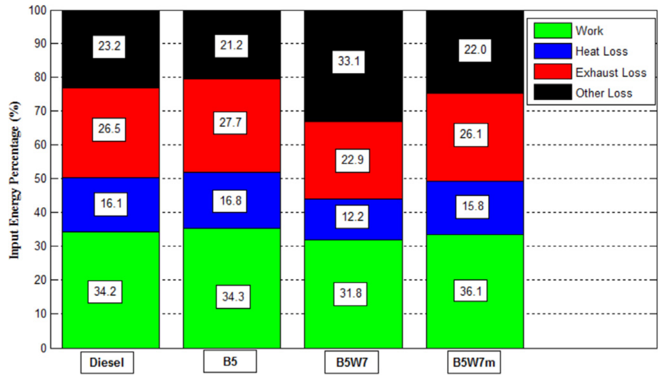

Fig. 5. Energy distribution for the various fuelling cases at 100% engine load.

Table 5
BTE comparison for various fuelling cases.

Engine load	Fuel blends			
	Diesel	B5	B5W7	B5W7m
25%	30.7	31.1	28.6	32.10
50%	32.6	33.1	30.2	33.8
75%	35.9	36.3	32.2	36.6
100%	34.2	34.3	31.8	36.1

B5W7, BSFC was enormously enhanced. Based on Fig. 6, the BSFC values of B5 and B5W7 were 8% and 23% higher than that of B5W7m, respectively. In fact, due to the positive correlation between BTE and BSFC, the positive impact of cerium oxide nanoparticles on increasing the BTE could be the reason for more favorable BSFC results. The combustion of neat biodiesel containing 5 and 10% water and aluminum nanoparticles was investigated by Rao and Anand (2016) and their results also showed that the inclusion of aluminum nanoparticles into biodiesel-diesel blends containing water resulted in lower BSFC.

3.2. Analysis of engine-out emissions

The results of the engine-out emissions including CO, HC, NOx, and CO_2 are presented in this section for different fuelling strategies. Fig. 7 shows the emission level of carbon monoxide (CO) for all the loads of engine. In-cylinder temperature and the level of unburned mixture are driving factors determining the rate of fuel burning and oxidation and consequently the creation rate of CO species. Based on Fig. 7, adding biodiesel to diesel fuel (i.e., B5fuelling case) led to 8% decrease in CO emission level on average, which was consistent with the findings of the majority of the literature (Kim and Choi, 2010). The combustion phenomenon is improved by the oxygen content of biodiesel, bearing a more complete combustion in another word which leads to a lower level of CO emission (Noehre et al., 2006). In contrast, CO emission was increased considerably with the inclusion of water into B5. Based on the data presented in Fig. 7, CO emission of the B5W7 fuelling case was about 40% higher than that of B5. Addition of water to fuel could alter the in-cylinder temperature leading to incomplete combustion and as a result, a higher level of CO emission. Similar results were also reported by Fahd et al. (2013) for the combustion of diesel in presence of water. However, the addition of CeO_2 nanoparticles into the fuel (B5W7m) decreased CO emission by 42% and 3% compared with B5W7 and B5, respectively. Based on the results depicted in Fig. 6, cerium oxide nanoparticles could have a positive effect on BSFC and as a result, could decrease the CO emission. In addition, premixed lean combustion of the mixture must have been improved by adding the CeO_2 nanoparticles leading to less incomplete combustion (i.e., lower CO emission) (Khalife et al., 2017b).

Emission data of unburned hydrocarbon (UHC) for B5, B5W7, B5W7m, and diesel fuelling strategies are presented in Fig. 8. The oxygen content of the B5 fuelling case led to an elevated temperature (in-cylinder) and thus, better combustion. In addition, the ignition delay was reduced due to higher cetane number of biodiesel, yielding reduced fuel-rich regions and consequently lowered UHC emissions (Noehre et al., 2006). Based on Fig. 8, B5 had about 8% lower UHC emission compared to neat diesel. Moreover, adding CeO_2 nanoparticles could improve the combustion quality and based on the results presented in Fig. 8, B5W7m fuelling case decreased UHC emission by 51% and 14% compared toB5W7 and neat diesel, respectively.

NOx creation in engine situation commonly depends on the availability of oxygen, mixture temperature, and existing time for reactions (Ozener et al., 2014; Gharehghani et al., 2017). As mentioned above, biodiesel molecular structure contains oxygen atoms. Aside from the biodiesel's oxygen content, the diesel-biodiesel blend has a higher cetane number, constituting imperative reasons behind a higher level of NOx emission. Based on the results presented in Fig. 9, higher mixture temperature led to lower amounts of NOx emission for neat diesel compared toB5 (Ozener et al., 2014). Accordingly, the major purpose of water addition in biodiesel-diesel fuel blends would be decreasing the NOx emission level. This reduction is ascribed to the lower in-cylinder temperature as presented in Fig. 3. Based on the data shown in Fig. 9, B5W7 emitted 30% lower NOx than B5. On the other hand, NOx emission

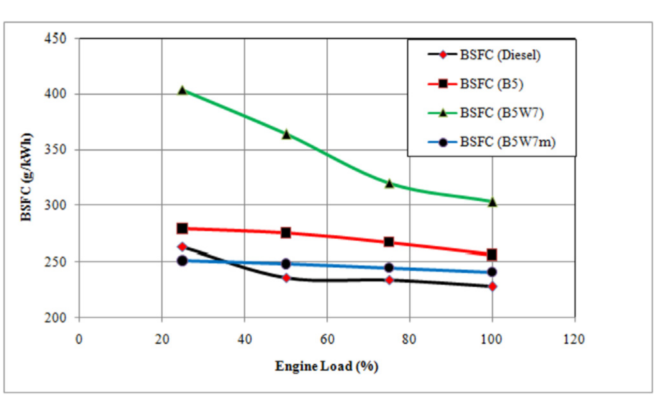

Fig. 6. BSFC results for different fuelling strategies.

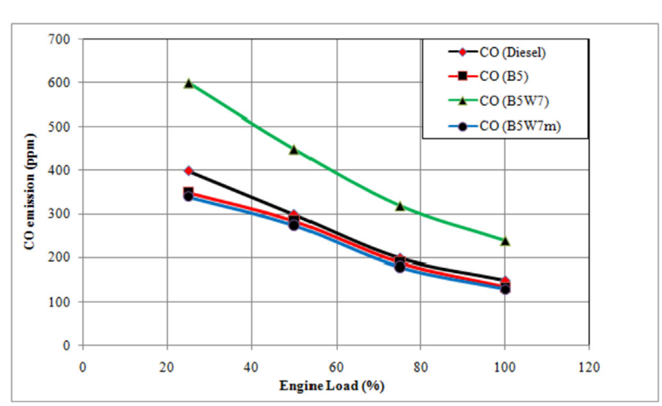

Fig. 7. The effect of water, biodiesel, and CeO_2 nanoparticles on CO emission.

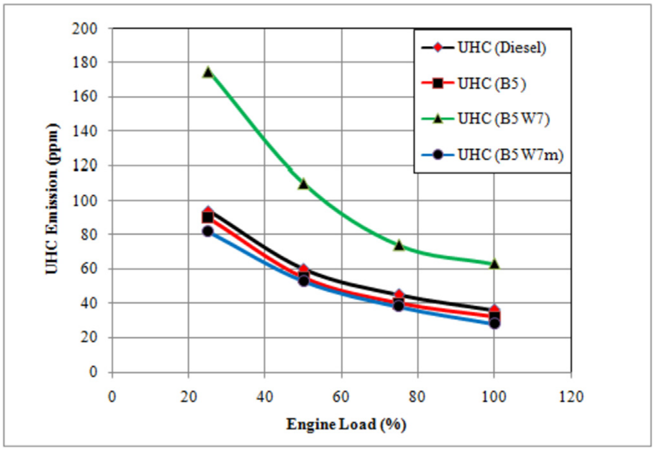

Fig. 8. The effect of water, biodiesel, and CeO_2 nanoparticles on UHC emission.

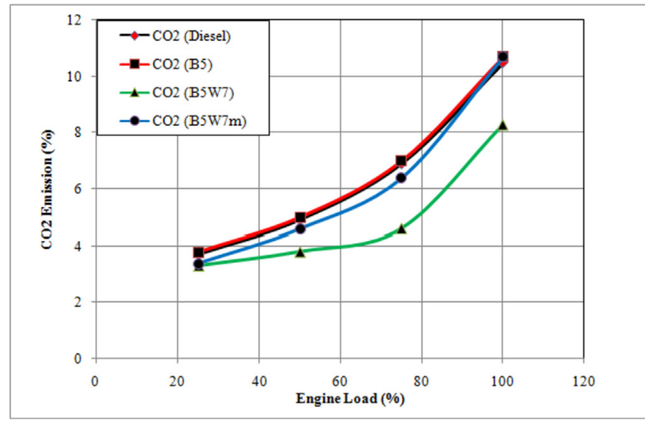

Fig. 10. The effect of biodiesel, water and CeO_2 particles on emitted CO_2.

was increased due to the addition of CeO_2 nanoparticles into the fuel blends, in comparison with B5W7 fuelling case. By the addition of 90 ppm CeO_2 nanoparticles into the B5W7, NOx emission was increased by 14%, but this value was still 21% lower than the NOx emitted through B5 combustion.

New emission policies require the emission concentrations to be lowered to under 10% by 2020 (Gharehghani et al., 2015). To weigh up the influence of water and CeO_2 nanoparticles on CO_2 emission, the results obtained for neat diesel, B5, B5W7, and B5W7mare presented in Fig. 10. B5 fuelling case led to negligible effects on CO_2 emission while B5W7 fuelling strategy was associated with about 25% lower emitted CO_2 compared with B5. This result was ascribed to the less complete combustion, due to less in-cylinder temperature for B5W7. On the other hand, by adding cerium oxide nanoparticles to fuel (i.e., B5W7m fuelling case), CO_2 emission was increased by about 22% compared with B5W7revealing a more complete combustion (i.e., lower CO and UHC emissions) for this fuelling case.

4. Conclusions

The effect of the simultaneous application of water (7 wt.%) and CeO_2 nanoparticles in diesel-biodiesel fuel blend at the start of injection of 20 BTDC was experimentally examined. Major conclusions of this study could be summarized as follows:

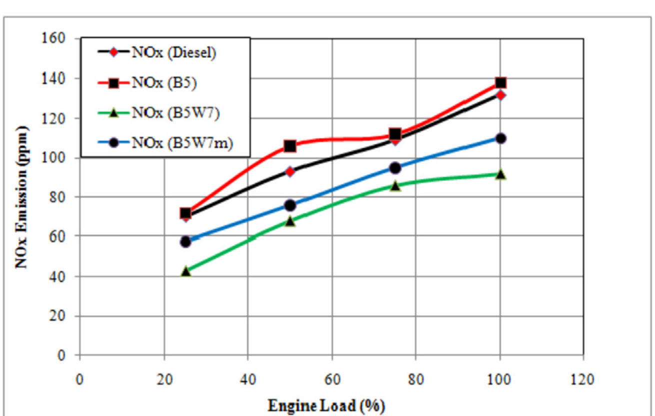

Fig. 9. The effect of water, biodiesel, and CeO_2 nanoparticles on NOx emission.

- B5W7m (B5 containing 7% water and nanoparticle) augmented brake thermal efficiency (BTE) by 13.5% and 6%, cmapred with those ofB5W7 and B5, respectively. This increase could be attributed to the positive effect of CeO_2 nanoparticles on the combustion process.
- The brake specific fuel consumption (BSFC) of B5W7m was 23% and 8% less than those of B5W7 and B5, respectively.
- B5W7m considerably lowered the CO emission; i.e., by 42 and 3% *vs.* those of B5W7 and B5, respectively. Cerium oxide nanoparticles could exerta positive effect on BSFC and as a result, could decrease the CO emission. In addition, premixed lean combustion of the mixture was improved by adding the CeO_2 nanoparticles leading to less incomplete combustion (i.e., lower CO emission)
- Adding CeO_2 nanoparticles could improve the combustion quality and based on the results obtained, B5W7m fuelling case decreased UHC emission by 51% and 14% compared with B5W7 and neat diesel, respectively.
- By including 90 ppm CeO_2 nanoparticles into B5W7, NOx emission was increased by 14%, this value was still 21% lower than the NOx emitted throughB5 combustion.
- Finally, B5W7m fuelling case was associated with 42% and 21% lower CO and NOx emissions compared with B5, respectively.

Overall, simultaneous addition of water (7 wt.%) and cerium oxide nanoparticles to diesel/biodiesel blend was found as an efficient solution to compensate for the unfavourable effects of high-level water inclusion on NOx emission and specific fuel consumption while maintaining the favorable effects on CO and HC emissions.

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Nomenclatures

AFR	air fuel ratio
B5	diesel containing 5% biodiesel
B5W7	diesel containing 5% biodiesel and 7% water
B5W7m	diesel containing 5% biodiesel, 7% water and 90 ppm CeO2

BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CAD	crank angle degree
CeO2	cerium oxide
CO	carbon monoxide
EGR	exhaust gas recirculation
ER	equivalence ratio
HC	hydrocarbon
HRR	heat release rate
IMEP	indicated mean effective pressure
NOx	nitrogen oxide
PM	particulate matter
PPR	pulses per revolution
rpm	revolution per minute
V	volume
WDE	water diesel emulsion
WBDE	water-biodiesel-diesel emulsion

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